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AEROSOL RESEARCH WITHIN THE ENVIRONMENTAL SCIENCE SECTION 1987 SUMMARY REPORT

Report No 88-82-K

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ABSTRACT

In 1986 the Research Division's Environmental Program Champion Task Group identified aerosol science as an area where Divisional expertise should be developed. To meet this need the Environmental Science Section embarked on establishing, in conjunction with other interested Sections, a centre of expertise in aerosol science. The approach taken was to acquire, and gain familiarity with, basic aerosol research tools, while developing research expertise by initiating research in one or two specific areas (eg, HEPA filter testing and nuclear safety). This report summarizes the progress made in 1987 and describes the equipment now available for generating and measuring aerosols. The following projects are suggested for the future: the development of methods for sampling aerosols in hostile environments; the implementation of an aerosol transport model; and the construction of a test rig for studying aerosols in large scale flows (flow rate up to about 4.7 m³/s).

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1.0 BACKGROUND

This report documents the effort made over the past year to establish a centre of expertise in aerosol science within the Environmental Science Section. This effort arose as a result of a recommendation from the Research Division's Environmental Program Champion Task Group that the Division needed to develop expertise in aerosol science (Anyas-Weiss et al, 1986).

Within the electric utility industry, an understanding of aerosol behaviour assumes generic importance in a variety of areas such as fugitive dust and fly ash emissions from coal-fired generation, the formation of photochemical smog and acid rain, reduction in atmospheric visibility due to pollution, insulator icing by freezing fogs, industrial hygiene, radiological health, nuclear safety analysis, and air cleaning and emission control technologies. Drift from mists, sprays or jets is also essentially an aerosol transport problem, whether, for example, in the unwanted spreading of toxic herbicides from spraying or in the transport of nongaseous radionuclides following a nuclear accident.

The term aerosol refers to particles small enough to be suspended in air (eg, Hinds, 1982; Hidy, 1984). Generally the term applies to particles between about $100\text{ }\mu\text{m}$ diameter, above which gravitational settling is rapid, and $0.001\text{ }\mu\text{m}$ diameter, below which one refers to molecular clusters. Aerosols can be of either solid or liquid composition and are usually termed coarse or fine depending on whether they are larger or smaller than about $2\text{ }\mu\text{m}$. Examples of naturally-occurring aerosols are bacteria, pollen, small dust particles, cloud and fog droplets and salt from sea spray. Aerosols can be formed or suspended by such processes as mechanical action, chemical reactions, combustion and sprays.

Because of their fine size, aerosols can be transported over long distances in the atmosphere. Aerosols can also play a very important and disproportionately large role in gas-solid interactions (such as heterogeneous chemical reaction or gas scavenging through dissolution in liquid drops). The reason for this is, perhaps, most easily demonstrated by an example. A 1 cm^3 volume of material dispersed into $0.1\text{ }\mu\text{m}$ diameter aerosols, will give rise to 1.9×10^{15} aerosols having a total surface area of 60 m^2 , representing an approximate 100,000 times increase in available surface area.

The report is organized as follows. Sectional objectives are stated followed by an overview of the progress made in 1987 towards meeting these objectives. A summary of available aerosol diagnostic and generation equipment and capabilities is given to inform potential users and clients. Finally, some recommendations for future work are made. Details of some work not reported elsewhere are recorded in the Appendix.

2.0 OBJECTIVES OF THE AEROSOL RESEARCH PROGRAM

The objectives adopted by the Environmental Science Section in response to the recommendations of the Environmental Program Champion Task Group were

- (1) to establish an aerosol research facility with the necessary instruments to generate and characterize aerosols in the laboratory and field; and
- (2) to develop expertise in aerosol science by initiating research into one or two areas of particular importance to Ontario Hydro.

As aerosol science is a truly interdisciplinary activity, an effort was made to cooperate with other interested Sections within Research Division (eg, Process Chemistry and Mechanical Testing and Development). Discussions were also held with potential stakeholders within Ontario Hydro to obtain their input to the planning process.

The progress made in 1987 towards meeting these objectives is outlined in the next Section.

3.0 OVERVIEW OF THE AEROSOL WORK PERFORMED IN 1987

Progress Towards Establishing an Aerosol Research Facility

Activities over the past year have established the foundations for the aerosol research facility. It is intended that this facility will eventually include the means to generate and characterize a wide range of aerosols under a variety of conditions.

Planning and acquisition of equipment has been pursued in co-operation with other Sections with the intent of developing a pool of equipment that is generally applicable to a wide range of problems.

In general, aerosol diagnostic and generation equipment for supermicron or coarse, and submicron or fine aerosols operate on different physical principles. Table 1 summarizes equipment available, or soon to be available, within the Environmental Science Section for these purposes. A brief description of each of these instruments and their capabilities follows. Table 1 also identifies some of the other equipment available within the Division.

TABLE 1
AEROSOL RESEARCH EQUIPMENT

<u>Purpose</u>	<u>Instrument</u>	<u>Specifications</u>
1) Aerosol Generation	TSI 9306 6-jet atomizer	0.04 to 4 μm Max generation rate, 7×10^{11} particles/min
	Atomizer (design of Liu and Lee, 1975)	0.032 to 1.3 μm (DOP)
	TSI 3450 (Vibrating orifice aerosol generator)	1.0 to 40 μm Highly monodisperse
	Spray nozzles (eg, Turbotak or Spraying System)	About 5 - 50 μm Polydisperse
2) Aerosol Concentration/Size Measurement	TSI DMPS (models 3071, 3020)	0.01 to 1 μm 0.1 to 10 ⁷ particles/cm ³
	PMS FSSP-100	1 to 95 μm
3) Others	Impactors, Dichotomous Samplers, Hi-Vol Samplers HEPA Filters, etc	

Aerosol Generation

The Environmental Science Section has obtained on loan a 6-jet atomizer (TSI 9306) from the Analytic Services Section and a vibrating orifice aerosol generator (TSI 3450) from the Process Chemistry Section. The Environmental Science Section is planning to acquire a 6-jet atomizer and a few spray nozzles. The characteristics of the 6-jet atomizer, the vibrating orifice aerosol generator, and spray nozzles are described below.

An atomizer (eg, 6-jet atomizer, TSI 9306) can be used to generate small-size aerosols (0.04-4 μm). This atomizer works on the same principle as the Collison atomizer. As shown in Figure 1, the pressurized air forms a high velocity jet through a small orifice. The pressure drop across the orifice causes the liquid to rise up the liquid tube. This liquid is then broken up into droplets by the high velocity air jet. Large droplets are removed by the spherical impactor. Smaller droplets are carried to the outlet where they are mixed with the dilution air. Up to 6 jets can be used. The aerosol size depends on the concentration of the atomizing solution, whereas the aerosol concentration depends on the input air pressure and the number of jets used.

1. Atomizer Jet
2. Liquid Tube
3. Pressurized Air In
4. Spherical Impactor
5. Dilution Air In
6. Aerosol Outlet Tube
7. Drain
8. Atomizer Liquid

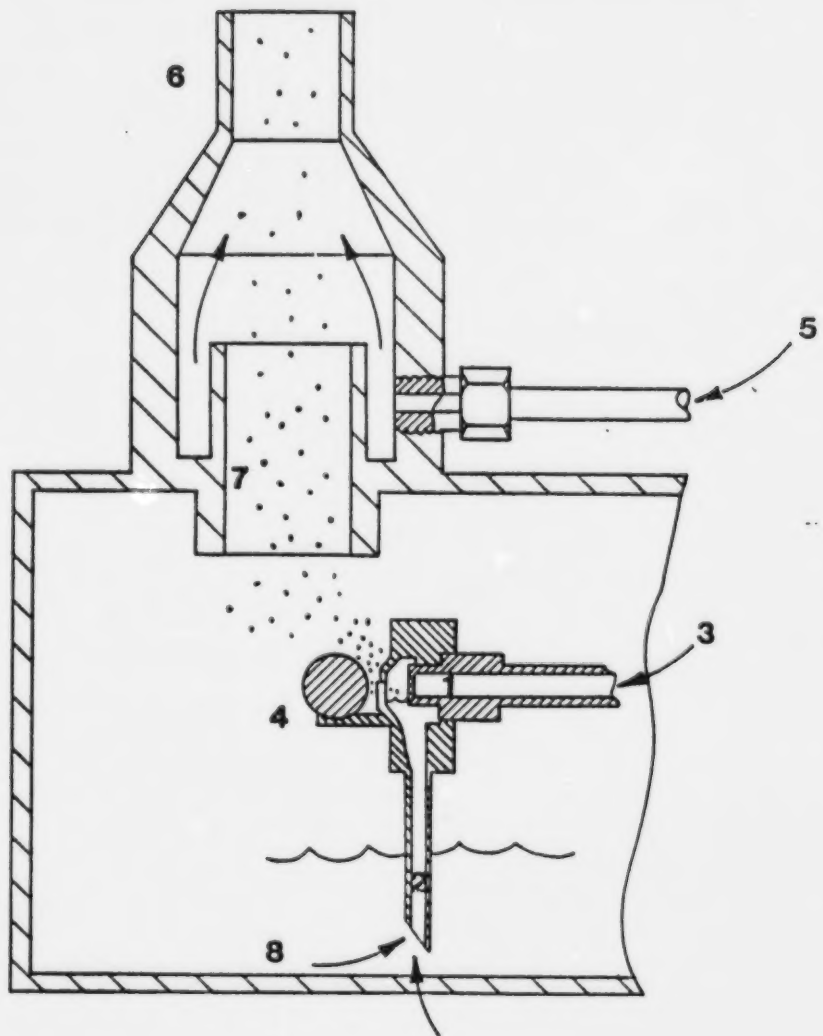


FIGURE 1
SCHEMATIC OF TSI MODEL 9306 SIX-JET ATOMIZER

This atomizer can provide a driving pressure up to 60 psi (400 kPa) but operates best at an input air pressure between 35 and 65 psi. An input pressure of 40 psi is commonly used for ambient atmospheric conditions. The atomizer has a built-in pressure regulator and gauge for control of input pressure, and a built-in rotameter and valve to regulate the flow of dilution air.

A single jet atomizer based on the design of Liu and Lee (1975) was also constructed, however operating experience with this device is limited.

A vibrating orifice aerosol generator (eg, TSI 3450) can be used to generate highly mono-dispersed supermicron aerosols (1.0 - 40 μm), with an optional large orifice being available to generate large-size aerosols (up to 200 μm). This generator operates on the instability and, eventually, breakup of a cylindrical liquid jet. The breakup process can be controlled precisely by applying a periodic disturbance of an appropriate frequency to the liquid jet. The generator performs four functions (Figure 2):

- (1) produces a liquid jet through a small orifice,
- (2) applies a controlled periodic disturbance to the orifice disc,
- (3) disperses the droplets to prevent coagulation, and
- (4) dilutes the aerosol.

The diameter of the final aerosol depends on the nonvolatile solute concentration in the jet solution and the initial droplet diameter; the aerosol generation rate depends directly on the operating frequency. Typical aerosol generation rates are about 1.0×10^7 particles/s (aerosol size of about 25 μm). This instrument has a built-in syringe pump for liquid delivery, frequency generator and counter, and vibrating orifice aerosol generation assembly.

Spray atomizing nozzles can also be used to generate large quantities of polydisperse supermicron liquid aerosols. They are fairly inexpensive. Depending on the inlet air pressure (about 10-90 psi) and liquid pressure (about 10-60 psi), the nozzles can cover a wide range of liquid droplet diameters (about 5-50 μm).

Aerosol Concentration/Size

The Environmental Science Section has acquired, or is planning to acquire, the equipment necessary to measure the concentration and size of both coarse (supermicron) and fine (submicron) aerosols.

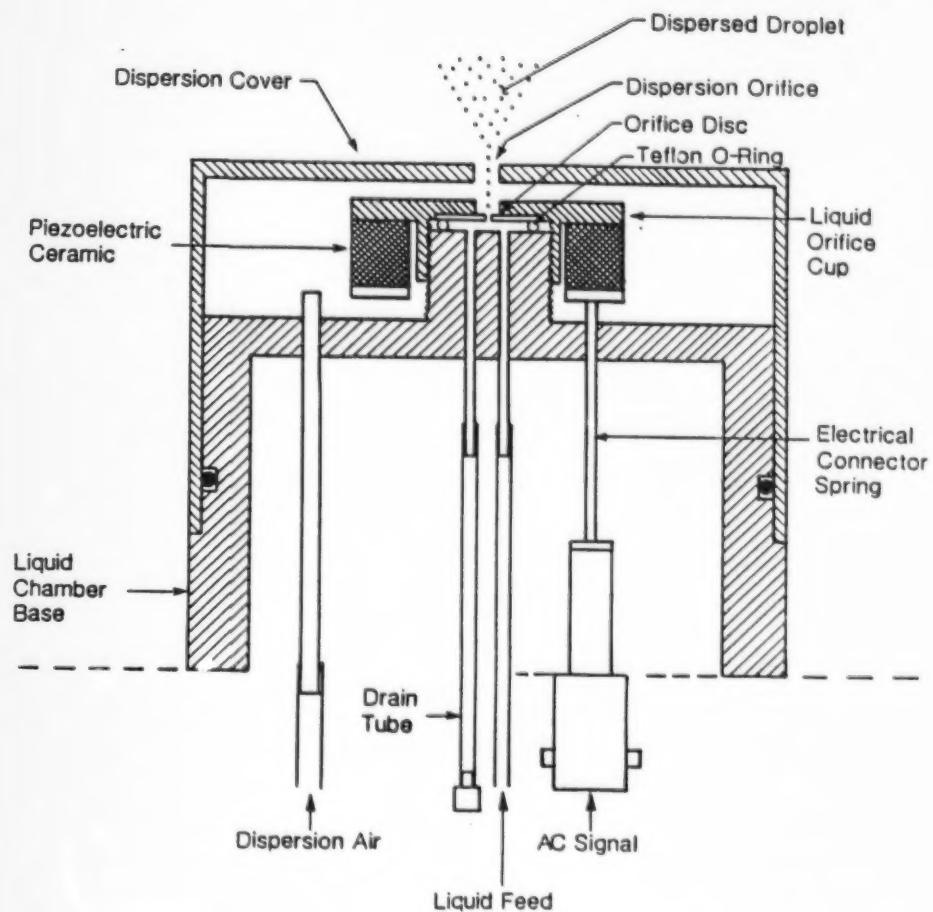


FIGURE 2

**SCHEMATIC DIAGRAM OF THE DROPLET DISPERSION SYSTEM
FOR THE TSI MODEL 3450 VIBRATING ORIFICE AEROSOL GENERATOR**

The TSI DMPS (Differential Mobility Particle Sizer) system offers high resolution and precise submicron aerosol size and concentration data. The DMPS (Figure 3) comprises an EC (Electrostatic Classifier) to size particles according to their mobility over 39 size channels, covering the range from 0.01 to 1.0 μm and a CNC (Condensation Nucleus Counter) to detect submicron particles independent of their original size. It can measure particle concentrations between 0.1 to 10^7 particles/ cm^3 .

Aerosol which enters the EC passes first through an initial impactor to remove large particles ($>1 \mu\text{m}$), and then through a neutralizer. The function of the neutralizer is to provide an equilibrium aerosol charge distribution. The EC consists of two concentric cylindrical electrodes. A high negative voltage is applied to the centre electrode. This voltage supply is controlled by the PC control system.

The outer electrode is kept at ground potential. Particle-free sheath air enters through the inner core whereas the aerosol passes through the outer annulus. Positively-charged particles are then collected on the negatively charged centre electrode. The trajectory of such a particle depends on the flowrate, electric mobility, electric field and analyzer geometry. Only those particles within a narrow mobility range pass through a slit near the bottom of the centre electrode. These particles are carried out of the EC to be counted by the CNC.

The CNC consists of a saturator, condenser, light scattering particle sensor, flowmeter and pump (Figure 4). Aerosol passes first through the saturator and then the condenser. During this time, vapour condenses on the particle to form a larger droplet. Each droplet is large enough to scatter a detectable amount of light when it passes through a light beam. The CNC has two modes of counting:

- (1) single particle counting for particle concentration below 10^3 particles/ cm^3 , and
- (2) photometric counting for particle concentration between 10^3 and 10^7 particles/ cm^3 .

The PMS FSSP (Particle Measuring Systems, Forward Scattering Spectrometer Probe) system measures supermicron particles in four overlapping size ranges. Each size range is divided into fifteen linear size intervals, providing up to 60 size channels in the 1 to 95 μm range. The probe is normally set up to size particles having velocities from 10 to 125 m/s. An additional fan-powered aspiration system can be used to provide a uniform velocity of approximately 26 m/s. The FSSP system is usually used to measure concentrations of $10^3/\text{cm}^3$ or less. The FSSP optical system is shown in Figure 5.

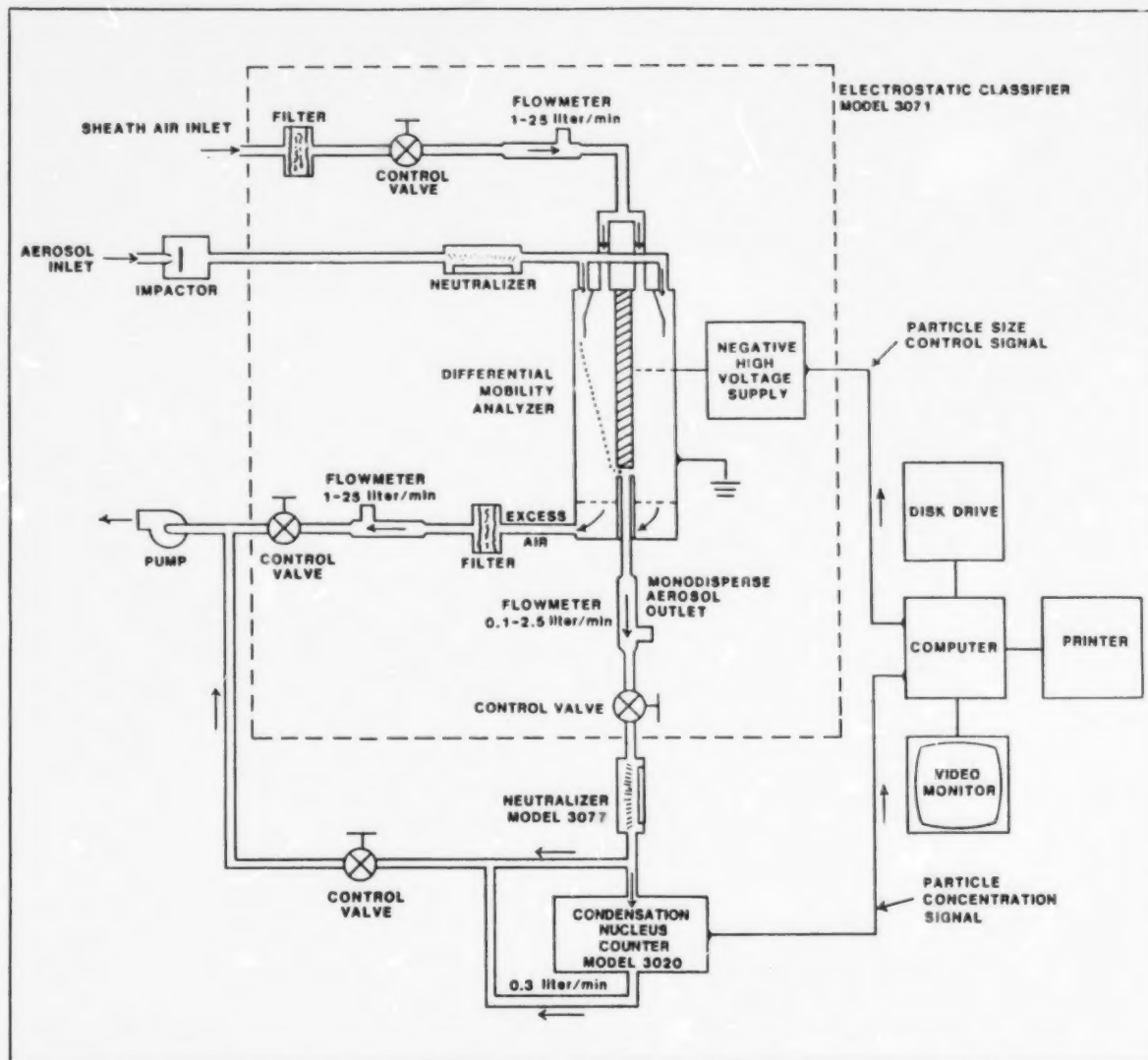


FIGURE 3

DIFFERENTIAL MOBILITY PARTICLE SIZER FOR MEASURING
SIZE DISTRIBUTION OF 0.01 - 1 μm PARTICLES

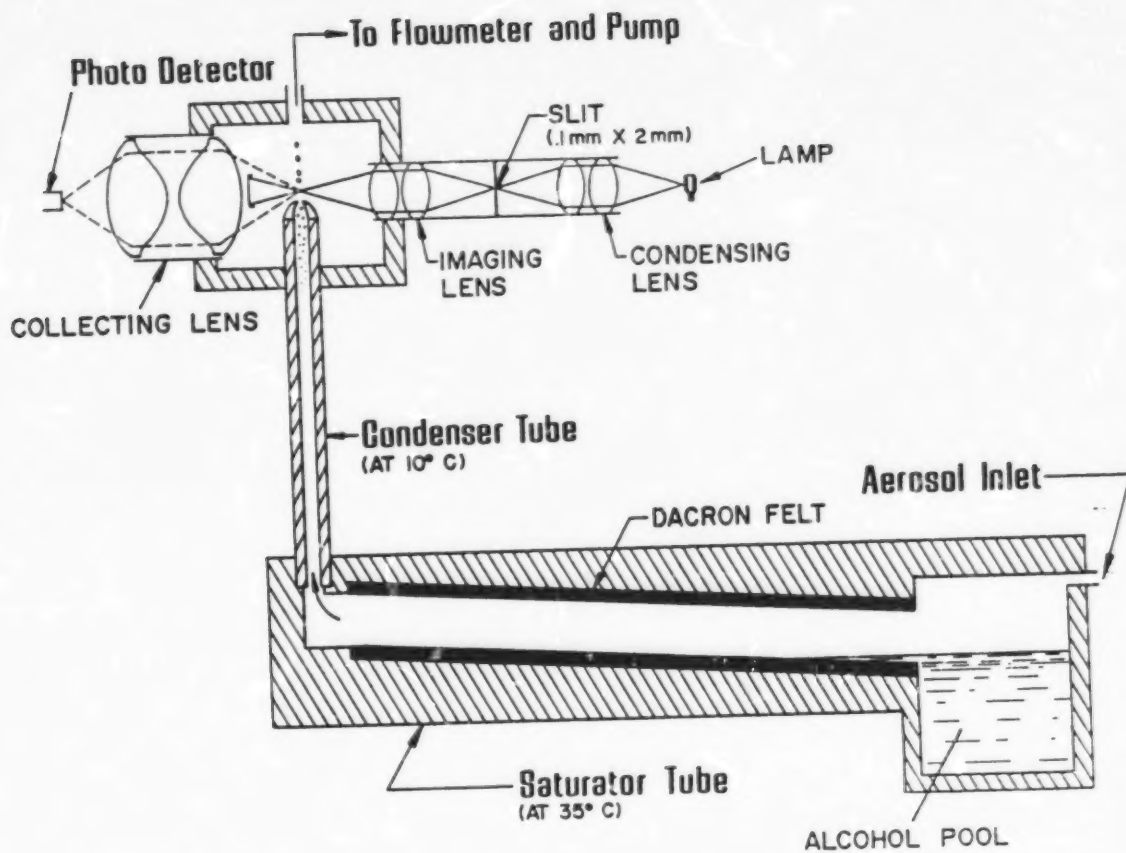


FIGURE 4

SCHEMATIC OF TSI MODEL 3020 CNC

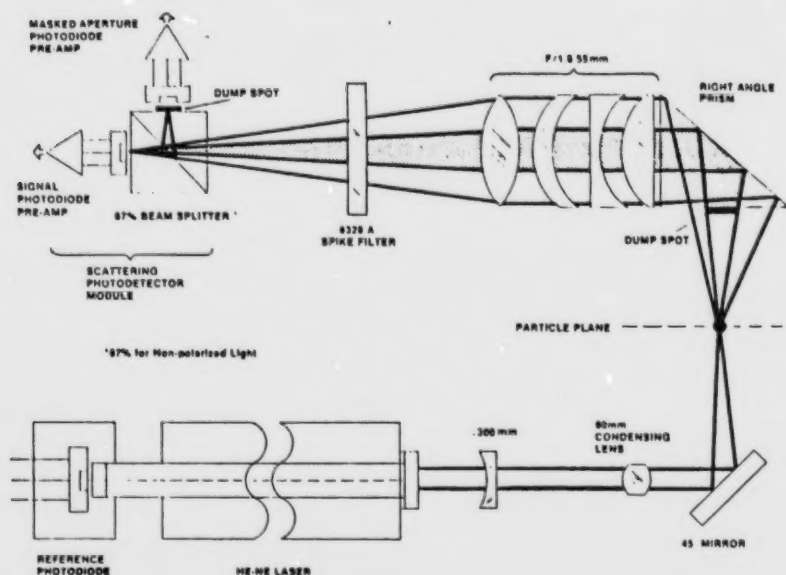


FIGURE 5

FSSP 100 OPTICAL SYSTEM DIAGRAM

The laser used is a high order multimode He-Ne tube (632.8 mm) with condensing optics. Particles passing through the laser beam in the sampling aperture, scatter light into the collecting optics. The amount of scattering depends on the particle size and laser mode.

Together, the TSI DMPS and the PMS FSSP systems allow a wide range of particle sizes (0.01-95 μm) to be measured. These two systems are interfaced with a PC/AT system for data acquisition.

HEPA Filter Testing

HEPA filters play an important role in many air cleaning applications ranging in scale from the personal respiration canisters used to avoid the inhalation of toxic dusts to the large filters used in building ventilation systems and Emergency Filtered Air Discharge Systems (EFADS) in nuclear stations.

There is often a need to verify filter performance under normal operating conditions or to obtain information on filter performance under extreme conditions, eg, operation for long periods or at high temperature and high humidity. Work in this field was started in a modest way by assembling a system to characterize the performance of the small HEPA filters used in respiration systems. The test system is shown in Figure 6. An atomizer, dryer, neutralizer chain was used to generate submicron aerosols of DOP (dioctyl-phthalate) and NaCl in various size ranges. These were either passed through the filter under test or through a bypass loop. The resulting aerosol size distributions were measured using the Electrostatic Classifier and Condensation Nucleus Counter. The EC/CNC combination is particularly suited to filter testing because of its high resolution and dynamic range.

Example spectra for a DOP aerosol measured upstream and downstream of a commercially-available respiration canister HEPA filter are shown in Figure 7. The DOP aerosol was generated by an atomizer (TSI 9306) using a 1% solution of DOP in ethanol.

The fractional penetration ($1 - \text{efficiency}$) of aerosols through the HEPA filter can be calculated from these spectra. Fractional penetration curves calculated from this run as well as other runs at different flow rates are shown in Figure 8. The characteristic minimum in filter efficiency (maximum in penetration) at about $0.2 \mu\text{m}$ can be seen as well as a strong decline in efficiency with flow rate. A curve giving aerosol penetration over a larger diameter range can be generated by using source solutions of different concentration to obtain initial size distributions peaked at higher or lower diameters, as required.

Aerosols and Nuclear Safety

An active and important area of research is the investigation of the behaviour of liquid aerosols formed in containment by a loss of coolant accident (LOCA). An understanding of aerosol behaviour in this situation is important because aerosols may act as carriers of non-gaseous radionuclides and therefore are responsible for transport of these species within containment and their release to the environment.

As aerosol transport behaviour is strongly dependent on size, it is important to know size distributions. In the past year a PMS-FSSP has been applied to size liquid aerosols in experimental studies of aerosol processes of importance to nuclear safety analysis.

The PMS-FSSP is a supermicron aerosol sizing device (see previous discussion) commonly used on board aircraft to measure cloud drop sizes and in the laboratory to characterize liquid sprays.

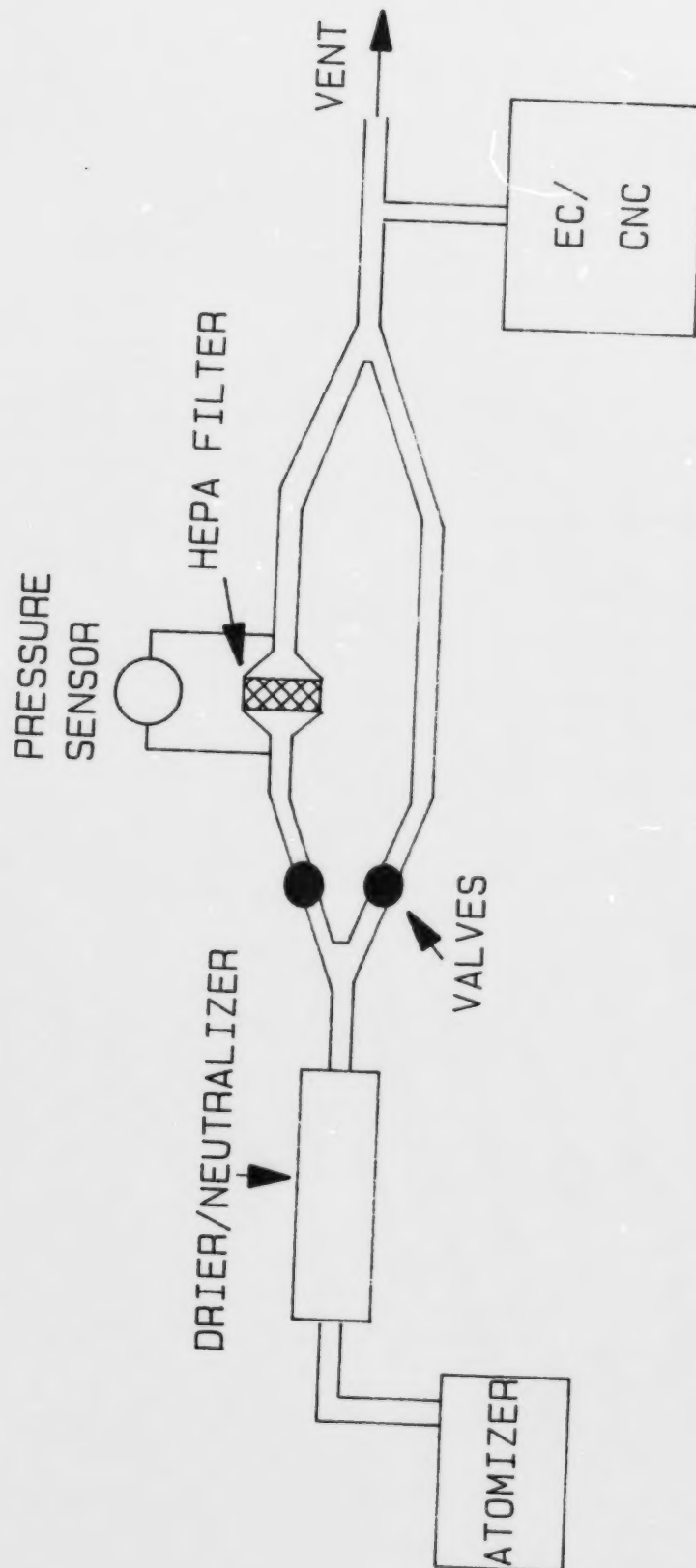
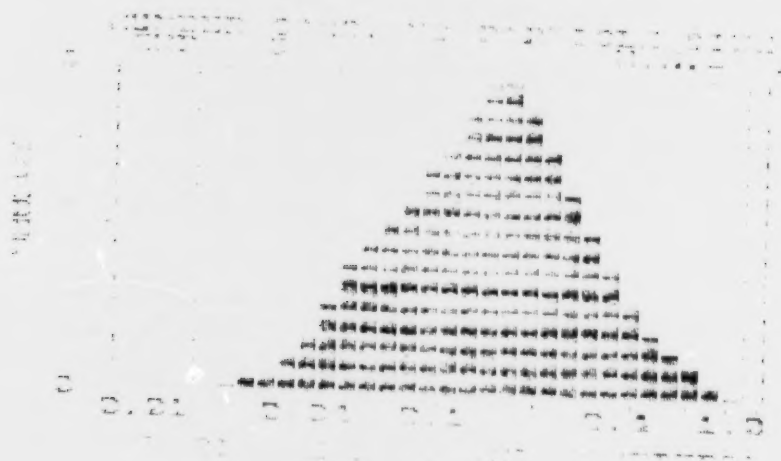


FIGURE 6
SCHEMATIC OF APPARATUS FOR TESTING
RESPIRATION CANISTER HEPA FILTERS

Before Filter



After Filter

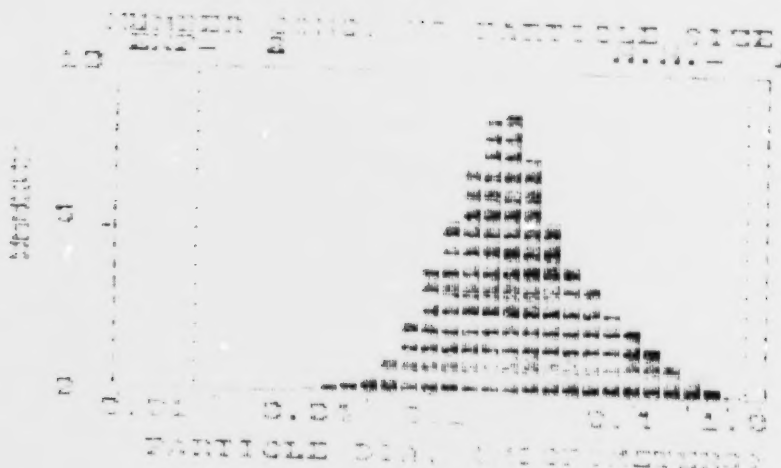


FIGURE 7

DOP AEROSOL SIZE DISTRIBUTIONS
MEASURED BEFORE AND AFTER PASSAGE THROUGH A
RESPIRATION CANISTER HEPA FILTER - FLOW RATE 66 LPM

FILTER PENETRATION - 1 % DOP

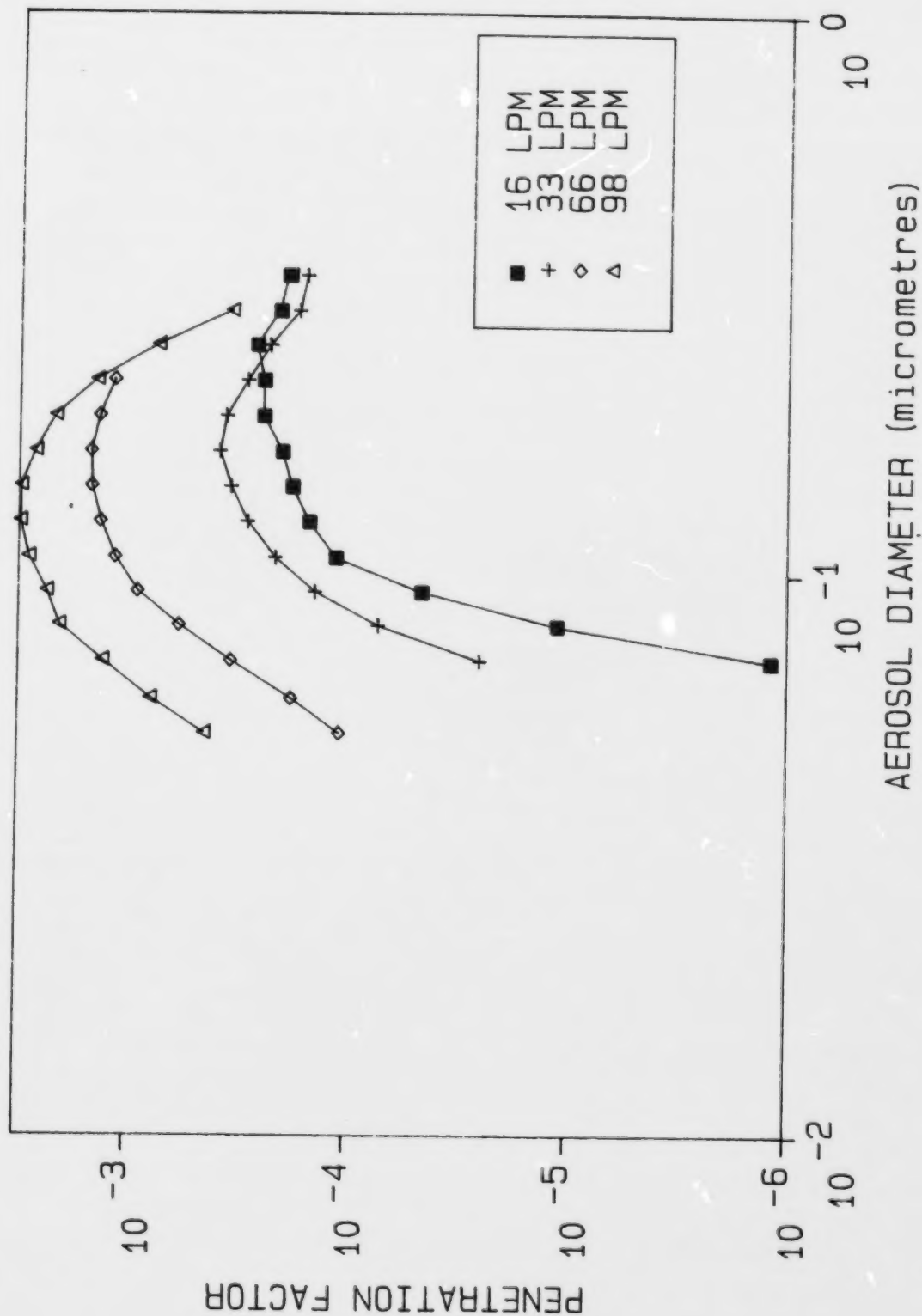


FIGURE 8
 FILTER PENETRATION FACTOR VS AEROSOL DIAMETER AT VARIOUS FLOW RATES
 FOR A RESPIRATION CANISTER HEPA FILTER

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The Environmental Science Section had obtained a FSSP on loan from the Atmospheric Environment Service of Environment Canada to measure fog droplet sizes in a study of insulator flashover caused by icing (Tam and Melo, 1986). During the past year, as a result of discussions with Nuclear Studies and Safety Department (NSSD), it became apparent that the instrument might be capable of providing valuable information on aerosol size distributions in experiments designed to simulate aspects of a loss of coolant accident. These experiments involved a jet of superheated water exhausting into a containment volume. To investigate the possibility of using this instrument, some preliminary measurements were made in the blowdown apparatus operated by the Mechanical Development and Testing Section for the Steam-Water Iodine Partitioning Experiment (Elphick and Russell, 1988). Preliminary results are given in Appendix A.

As these tests were promising, funding was obtained to use the FSSP to measure aerosol size distributions in the Water Aerosol Leakage Experiment (WALE). The sampling problem posed was formidable - aerosols had to be extracted from a vessel containing steam. In the first series of experiments a vertical thin wall sampling tube was used. The tube was heated to avoid condensation. A sufficient sampling flow was developed by the pressure differential between the vessel and the outside atmosphere. Droplet size distributions at present are relative as the absolute sampling efficiency is not known as a function of aerosol size. We hope to determine the sampling efficiency directly by simulating aspects of the sampling set up in the laboratory using a well-characterized aerosol. These results will be reported as part of the WALE documentation.

Proposals were also submitted to NSSD to carry out aerosol sizing in further experiments in the WALE series, to study aerosol loss processes (particularly jet entrainment) in the WALE vessel using a separately injected labelled aerosol, to study aerosol removal by tortuous flows and to carry out full-scale HEPA filter tests.

Large-Scale Aerosol Research Facility

Based on discussions within Research Division and with various stakeholders within Ontario Hydro it became apparent that a multipurpose aerosol research facility would be a valuable addition to the Division's capability. A plan for such a facility has been developed (Leung, 1988). Conceptually, this facility consists of a test rig with the capability of generating large-scale air flows of well-defined properties (flow velocity, temperature and relative humidity) containing well-characterized aerosols.

This facility will support basic aerosol research studies and at the same time will benefit a wide variety of ongoing projects such as full-scale HEPA filter testing, insulator icing studies and calibration of flow measuring devices.

The construction of the aerosol research facility is planned in three stages to study ambient, high temperature-high humidity, and low temperature conditions, respectively. After completion of these three stages, the aerosol research facility will provide the range of operating conditions listed below.

Temperature	-30 to 100°C
Relative Humidity	0 to 100%
Velocity	about 0.1 to about 15 m/s (near ambient temperature and RH conditions) about 0.1 to about 2.5 m/s (near 100 or -30°C)
Particle Size	0.04 to 1.0 μm (submicron particles) 1 to 40 μm (supermicron particles)
Concentration	about 10^4 particles/cm ³ at 0.472 m ³ /s total tunnel flow-rate (submicron particles)

A detailed design for the first stage of the facility was prepared by Leung (1988). The first stage will consist of two basic units - a tunnel (Figure 9) and a drive system. The tunnel will be constructed in modular fashion with the following functional units - bellmouth, aerosol injector, turbulence reducers, sampling sections and test section. The drive system will consist of a centrifugal fan with inlet vane and outlet damper control. System parameters such as humidity, temperature, velocity, flow rate, pressure drop, aerosol concentration and size will be collected and stored in a PC/AT control/data-acquisition system.

Construction of the first stage is expected to begin in early May and be completed by July 1988.

Aerosol Modelling

Mathematical models of aerosol behaviour (eg, ANS 1984; Jordan et al, 1981; Jordan and Kuhlman, 1985; Gelbard and Seinfeld, 1980; Gelbard, 1987) usually describe the evolution of the aerosol size distribution for aerosols undergoing one or more of the following processes:



- coagulation,
- deposition,
- impaction,
- condensation,
- nucleation, and
- evaporation.

Details of these processes and how they are parameterized in typical models can be found in the cited references. Most models assume a homogeneously mixed volume (or volumes connected by gas flows.) Models that treat all processes by the simplest of systems rapidly become very complex and computer-intensive. The field of aerosol model development is therefore still a very active one.

As part of a short course on aerosol modelling on personal computers a copy of the MAEROS II code was obtained. This code is written in Fortran IV and was developed for the US Nuclear Regulatory Commission (Gelbard, 1987a). The code treats coagulation (Browian, gravitational and turbulent) and deposition (gravitational, diffusive and thermophoretic) of aerosols in a volume of given dimensions and temperature, contained by walls of a given temperature. Modules are being added to treat condensation and evaporation processes (Gelbard, 1987b) which may be very important in dealing with liquid aerosols. A revised code will be obtained when available.

Ground Contamination Study

To provide input to nuclear emergency planning within Ontario, an analysis of the potential surface contamination arising from a hypothetical accident was carried out (Fluke et al, 1987). For the scenarios considered (predicted frequency down to once per million reactor years), it was found that ground contamination is a small component of the total potential radiological impact.

A significant pathway for surface contamination is the deposition of aerosols from the atmosphere. Aerosol deposition rates depend on the size of the aerosol and surface and atmospheric conditions. As input to this study, expressions for aerosol deposition velocity and precipitation scavenging rate as a function of these parameters were developed (Ogram, 1986) based on the correlations given by Sehmel (1984). These expressions were compared to available experimental data and found to agree relatively well.

4.0 RECOMMENDATIONS FOR FUTURE WORK

We should continue to develop an aerosol research capability by implementing and gaining familiarity with appropriate experimental and theoretical research tools and by carrying out research in selected areas. Opportunities for transfer funding are expected to increase given the diversity of fields where an understanding of aerosol behaviour is important. Some specific recommendations are listed below.

(1) Improve Supramicron Aerosol Sampling Methods

A need exists to improve techniques for sampling aerosols in hostile environments such as steam flows or burner and stack atmospheres. This need is particularly urgent in regard to supermicron or volatile aerosols which are easily lost or perturbed in a sample extraction process. To minimize these problems sampling systems should be adapted to in-situ operation. Where this does not appear feasible, a better understanding of the perturbations introduced by the sample extraction process needs to be established, perhaps by controlled experiments in the laboratory. For example, the adaptation of the PMS-FSSP to allow absolute water aerosol concentration measurements in steam flows would be very valuable. If successful, this is likely to find other applications.

(2) Construct the Aerosol Test Rig

The multipurpose test rig design and location should be finalized in consultation with other interested Sections and potential clients within the Corporation. This will establish a facility for aerosol tests in the large-scale flows (flow rate up to about $4.72 \text{ m}^3/\text{s}$). This facility will support a number of important projects, including full-scale HEPA filter testing, aerosol impingement on insulators and aerosol retention in tortuous flow paths.

(3) Implement and Maintain the MAEROS Aerosol Code

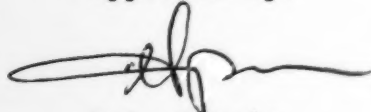
A computer code for aerosol behaviour will be of great value in planning and interpreting experimental studies of aerosol behaviour. Ideally, this code should be capable of dealing with major deposition and coagulation processes, condensation and evaporation, aerosol chemical composition and gas flow patterns. MAEROS, being actively under development for the US Nuclear Regulatory Commission, is a suitable state-of-the-art code for use as a research tool.

(4) Research Aerosol Processes

As the trapping and escape of aerosols containing hazardous material is very strongly dependent on aerosol size, an improved understanding of aerosol formation and removal processes as a function of aerosol diameter will be beneficial. Areas of immediate relevance include jet flashing, flow shearing, turbulent

coagulation and aerosol trapping and deposition in tortuous flows or in flows past objects of complex geometry. In the area of nuclear safety analysis any studies that improve the understanding of small-scale experiments (eg, WALE) and thereby help scale up the results, will be very useful.

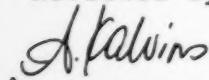
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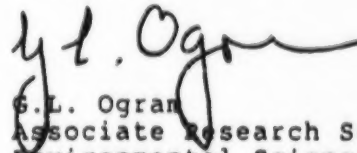
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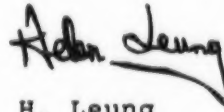


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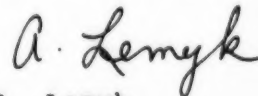
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APPENDIX A

MEASUREMENTS OF AEROSOL SIZE DISTRIBUTIONS IN THE BLOWDOWN EXPERIMENTS OF APRIL 16 AND MAY 12, 1987

A1 EXPERIMENTAL CONDITIONS

In order to investigate the suitability of the PMS-FSSP (Particle Measuring Systems - Forward Scattering Spectrometer Probe) for measuring the size of liquid water aerosols resulting from blowdown experiments, some preliminary measurements were made in the apparatus operated by the Mechanical Research Department of Ontario Hydro Research (Elphick & Russell, 1987). A calibrated FSSP probe was loaned for this purpose by the Atmospheric Environment Service of Environment Canada. To ensure sufficient sampling velocity, the probe was always operated using the aspirated exponential sampling horn. The two sets of measurements obtained are described below.

A1.1 April 16, 1987

Measurements were made with the cyclone/demister/condenser chain in place. The sampling locations were

- (1) in the reflected jet at the cyclone inlet, at an angle of about 45° and approximately 20 cm from the inlet.
- (2) in the fine mist exiting the condenser at approximately 10 cm from the condenser outlet.

The boiler temperature was 232°C , corresponding to a pressure of 3 MPa, for all samples.

A1.2 May 12, 1987

The cyclone/demister/condenser chain was removed and measurements were made at two downstream distances (1.0 and 1.9 m) in the free jet expanding into the room. Samples were taken at the jet centreline and at 20 cm above and below the centreline. The latter points corresponded roughly to the upper and lower boundaries of the visible jet, respectively. The sampling time was 30 s in all cases.

The boiler temperature was 232°C , corresponding to a pressure of 3 MPa, for most samples.

A2 RESULTS

Aerosol size distributions measured in the reflected jet at the cyclone entrance are shown in Figures A1 and A2. A peak diameter of 14-16 μm was observed. As shown in Figures A3 and A4, the steam escaping the condenser was much finer. The distribution had a peak diameter of about 1 μm *.

Measurements in the free jet are shown in Figures A5 to A7. At 1 m it is clear that the centreline shows a higher fraction of large droplets ($>25 \mu\text{m}$ diameter) than the upper and lower parts of the jet (Figure A5). However, further downstream at 1.9 m this difference is not as marked, with the centreline distribution tending towards that observed near the upper and lower boundaries of the jet (Figure A6). At the end of the experiment the sample obtained at 1.9 m, +20 cm above the jet was repeated three times (runs 1, 2 and 4 in Figure A7). Reproducibility was found to be good, even though the boiler temperature decreased to 206°C, with a corresponding pressure decrease during these runs. (Run 3 was taken using a lower size range on the PMS probe and is normalized differently.) The trend is however similar in the overlapping size region.

To avoid wetting the FSSP excessively, a cardboard shield was mounted around the sampling horn, about 10 cm downstream of the entrance to the horn. The first run was carried out without this shield in place. The results are compared in Figure A8 to a run with the shield in place to give some idea of the effect of the shield on the observed size distribution. With the shield in place the distribution is shifted to the right by about 5 μm indicating perhaps that flow blocking causes reflection of larger particles upwards into the sampling horn, and that smaller particles tend to be deflected away from the entrance of the horn.

The peak diameter observed in the free jet was in most cases about 25 to 30 μm , slightly larger than that observed in the reflected jet at the cyclone inlet.

*Note that all plots show the number of counts per size range channel. Each channel includes aerosols with diameters ranging between the indicated value and the next point.

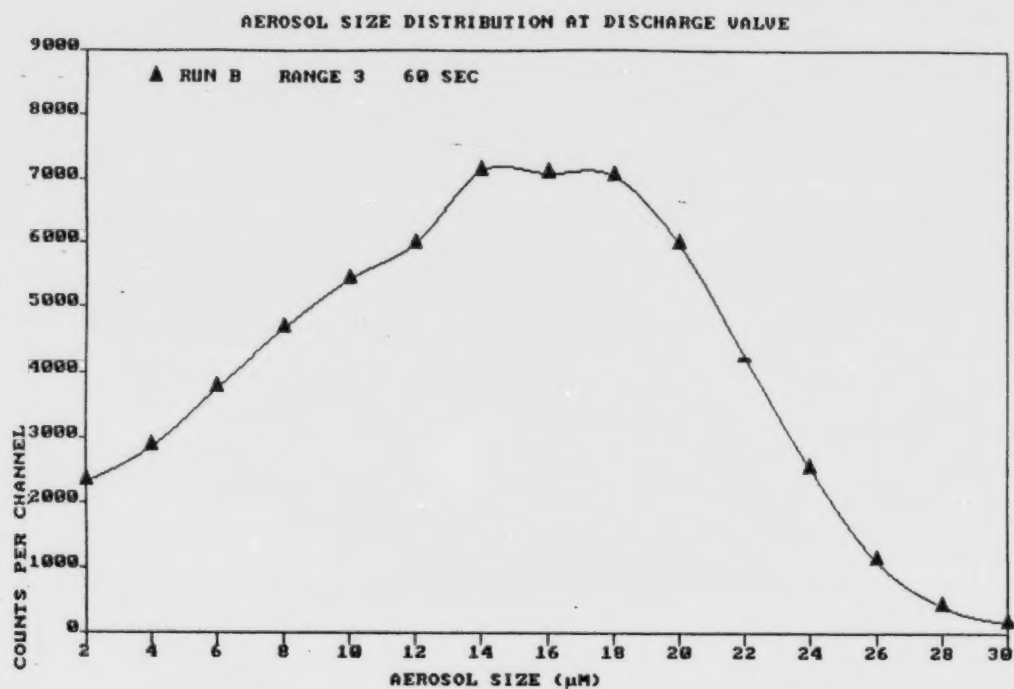


FIGURE A1

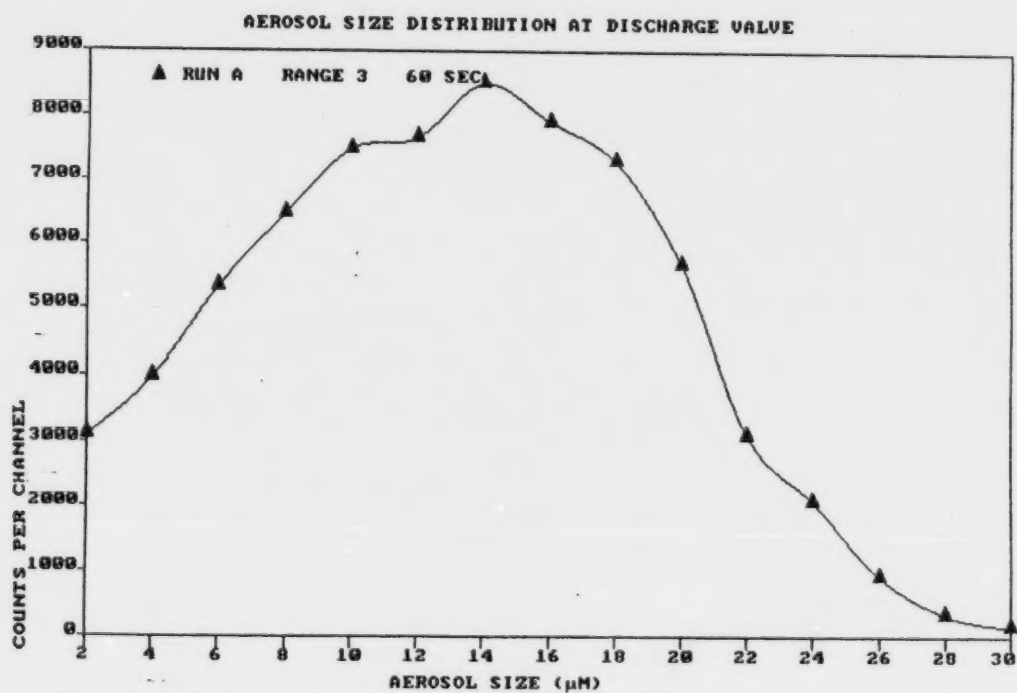


FIGURE A2

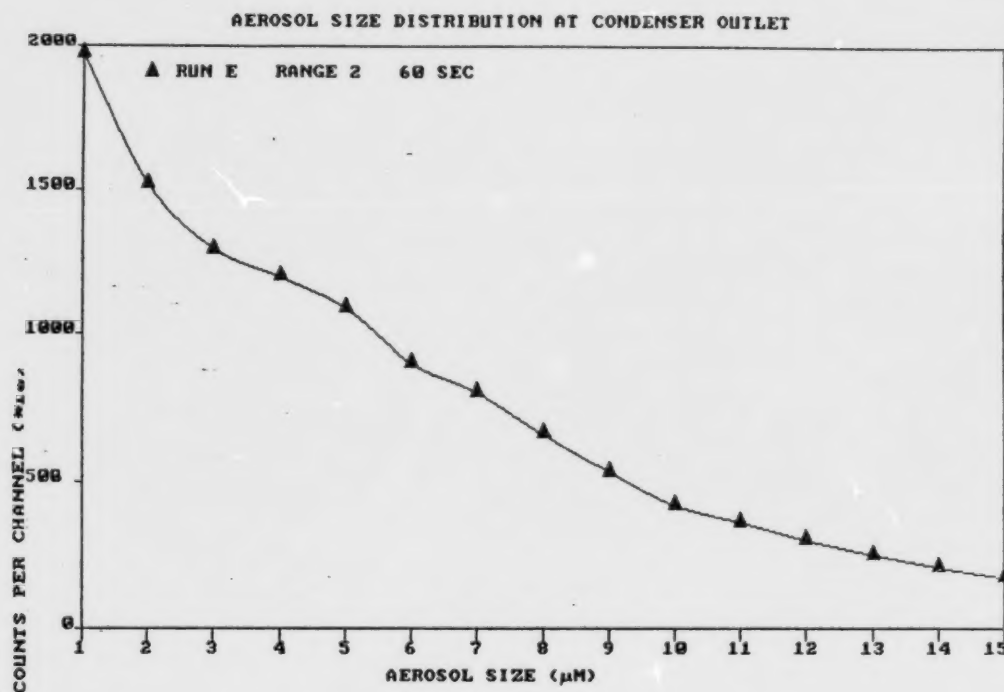


FIGURE A3

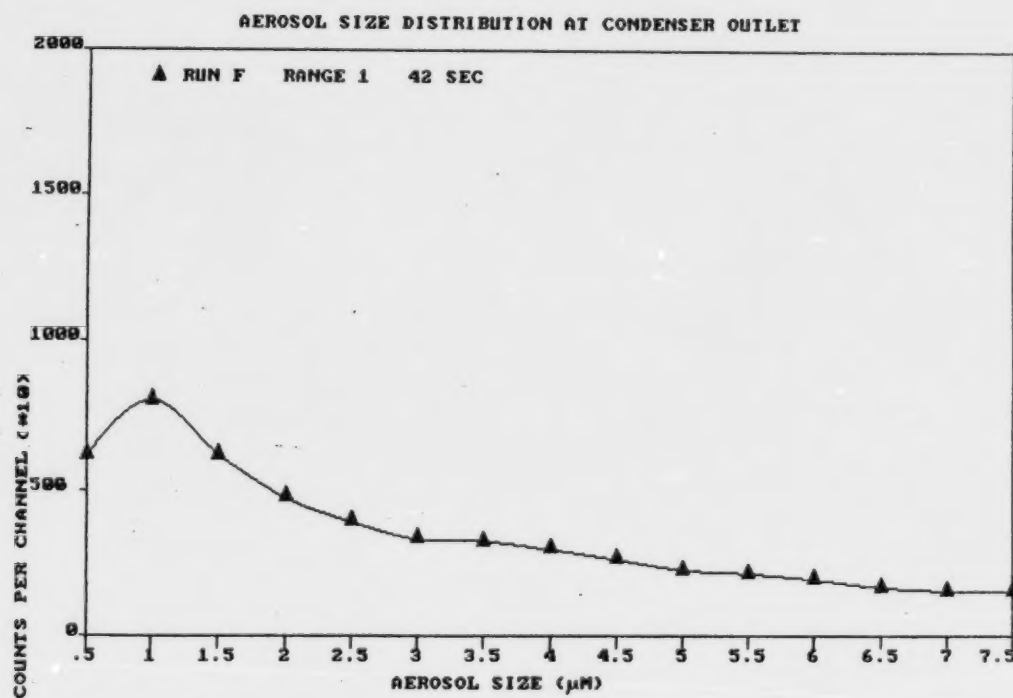


FIGURE A4

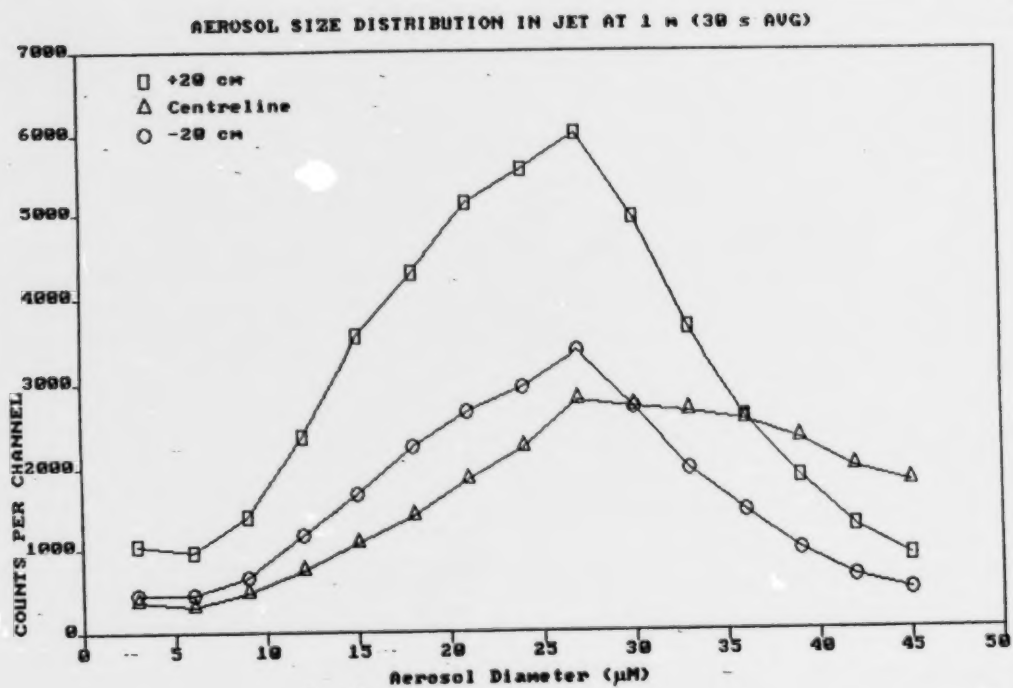


FIGURE A5

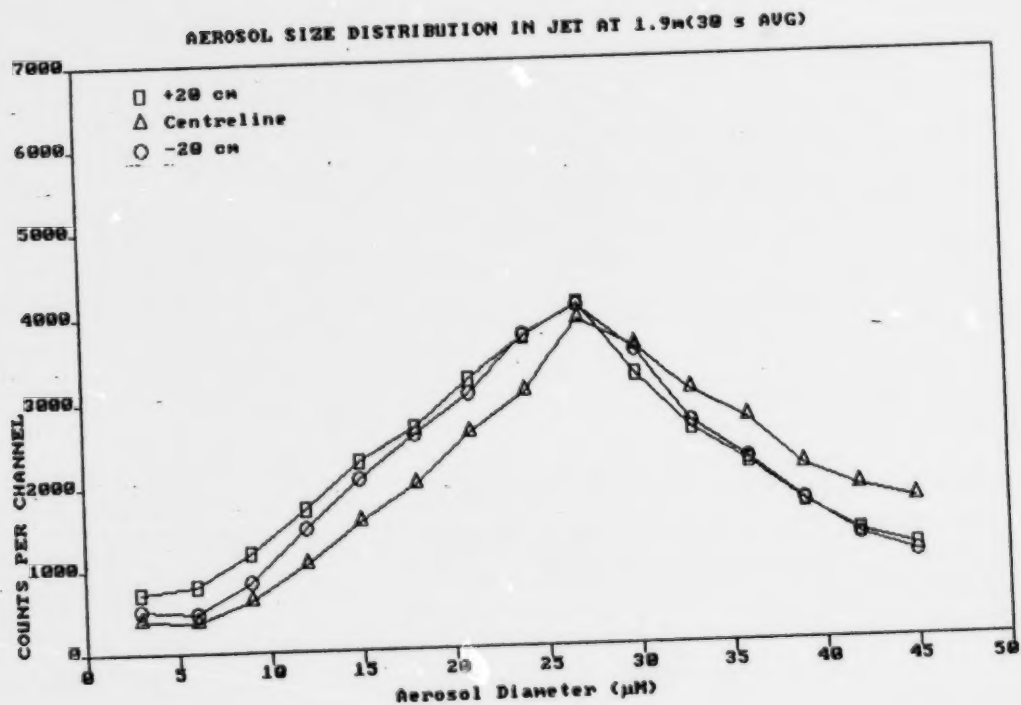


FIGURE A6

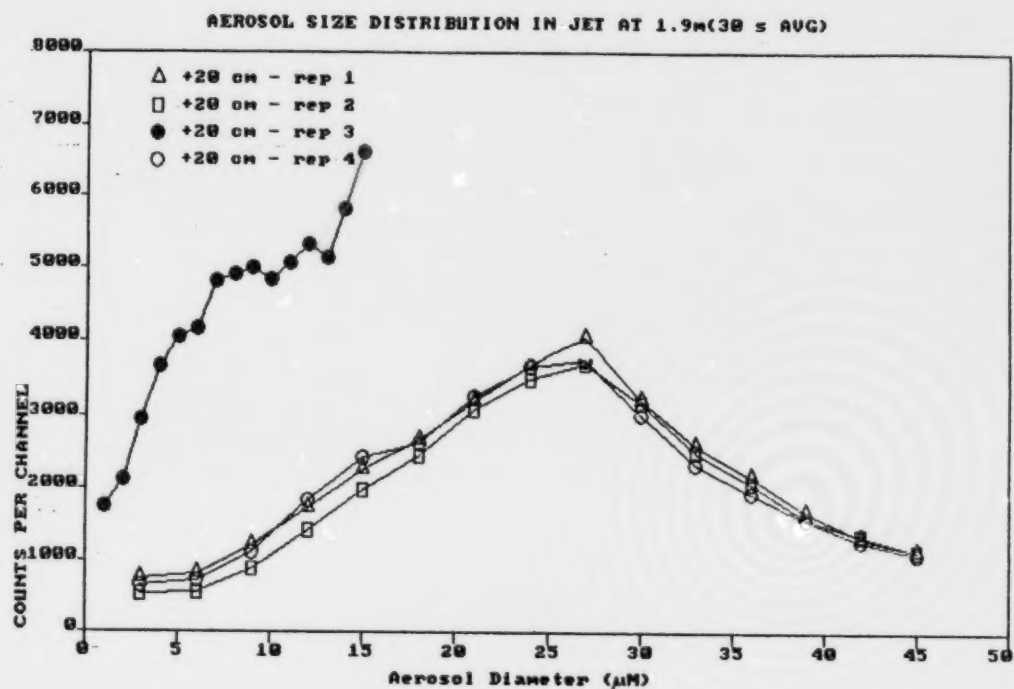


FIGURE A7

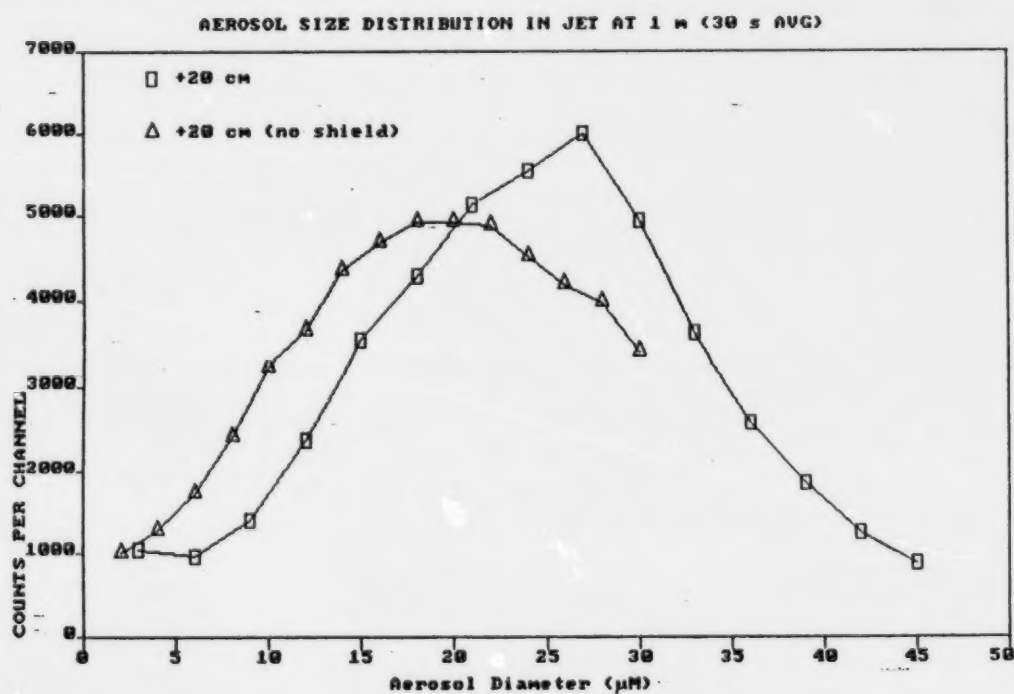


FIGURE A8